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Assessment of Environmental Sustainability in Highway Construction and Maintenance": A Review

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Abstract*: These activities can have significant impacts on the environment, including air and water pollution, habitat destruction, resource depletion, and contributions to climate change through greenhouse gas emissions. As awareness of these environmental challenges has grown in recent decades, there has been increasing focus on developing more sustainable approaches to highway infrastructure. Environmental sustainability in the context of highways refers to designing, building, and maintaining road networks in ways that minimize negative ecological impacts, conserve natural resources, protect human health, and support long-term environmental quality. This involves considering the full lifecycle of highways, from raw material extraction and construction to operation, maintenance, and eventual decommissioning. Key aspects include reducing emissions and pollution, using recycled and low-impact materials, minimizing land disturbance, managing storm water runoff, preserving habitats and biodiversity, and designing for climate change resilience.*

Keywords: activities, significant impacts, environment, including air, water pollution, habitat destruction, resource depletion, contributions climate change, greenhouse gas emissions

I. INTRODUCTION

The construction and maintenance of highways is essential for connecting communities, facilitating commerce, and enabling mobility in modern society. However, these activities can have significant impacts on the environment, including air and water pollution, habitat destruction, resource depletion, and contributions to climate change through greenhouse gas emissions. As awareness of these environmental challenges has grown in recent decades, there has been increasing focus on developing more sustainable approaches to highway infrastructure.

Environmental sustainability in the context of highways refers to designing, building, and maintaining road networks in ways that minimize negative ecological impacts, conserve natural resources, protect human health, and support long-term environmental quality. This involves considering the full lifecycle of highways, from raw material extraction and construction to operation, maintenance, and eventual decommissioning. Key aspects include reducing emissions and pollution, using recycled and low-impact materials, minimizing land disturbance, managing storm water runoff, preserving habitats and biodiversity, and designing for climate change resilience. Assessing the environmental sustainability of highway projects is crucial for setting goals, evaluating progress, guiding decision-making, and demonstrating accountability to the public. Sustainability assessment can occur at multiple scales, from evaluating specific materials and construction practices to analyzing the cumulative impacts of entire highway networks. A variety of sustainability rating systems, metrics, and tools have been developed for measuring and scoring the environmental performance of transportation infrastructure. The importance of environmental sustainability in highway construction and maintenance cannot be overstated. Highways have a massive spatial footprint, with the U.S. Interstate Highway System alone covering nearly 47,000 miles as of 2020 (Federal Highway Administration, 2020). Globally, the length of paved roads exceeds 40 million kilometers and continues to rapidly expand (International Road Federation, 2022). The materials used in roads, such as aggregate, asphalt, concrete, and steel, are typically mined and manufactured through energy and emissions-intensive processes. Highway construction often involves extensive earthwork and land disturbance that fragments natural habitats, alters hydrology, and increases erosion and sedimentation. According to one estimate, roads and highways are responsible for 15-20% of habitat fragmentation in the U.S. (Barton et al., 2014).

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Impervious pavement also contributes to stormwater runoff pollution, thermal pollution of waterways, and urban heat island effects. Additionally, vehicle emissions from traffic are a major source of air pollutants like particulate matter, nitrogen oxides, and volatile organic compounds, which have well-documented health impacts. From a climate change perspective, the transportation sector is one of the largest and fastest-growing sources of greenhouse gas emissions. In the U.S., transportation accounted for 27% of total emissions in 2020, with on-road vehicles making up over 80% of this share (Environmental Protection Agency, 2022a). Globally, on-road transport contributed 12% of total CO_2 emissions from fuel combustion in 2019 (International Energy Agency, 2021). While efforts to improve vehicle efficiency and electrify fleets are underway, addressing the sustainability of highway infrastructure itself remains critical.

II. ENVIRONMENTAL SUSTAINABILITY IN HIGHWAY

(i) Key Principles and Goals - At its core, environmental sustainability is about meeting the resource needs of current generations without compromising the ability of future generations to meet their own needs, as famously defined in the U.N. Brundtland Report (World Commission on Environment and Development, 1987). In the highway sector, this means designing, constructing, and maintaining road infrastructure in ways that support long-term environmental quality, ecosystem health, and climate stability. Several key principles and goals underpin the concept of highway sustainability:

Minimize negative environmental impacts: Sustainable highway projects should aim to avoid, minimize, and mitigate adverse effects on air, water, land, biodiversity, and human health throughout the lifecycle of the infrastructure. This includes reducing pollution emissions, preventing habitat loss and fragmentation, protecting water resources, and minimizing noise and visual impacts on communities.

Conserve natural resources: Highway construction is resource-intensive, utilizing large quantities of materials like aggregates, binders, and fuels. Sustainable approaches prioritize the efficient use of these resources, such as using recycled and renewable materials, optimizing designs to reduce material quantities, and implementing construction practices that minimize waste.

Support climate change mitigation and adaptation: With the transportation sector being a major contributor to greenhouse gas emissions, sustainable highway projects should strive to reduce their carbon footprint. This can involve using low-carbon materials and fuels, supporting low-emissions vehicles and transit, and implementing carbon sequestration measures. At the same time, highways must be designed to be resilient to the impacts of climate change, such as more frequent and severe weather events, sea level rise, and temperature extremes.

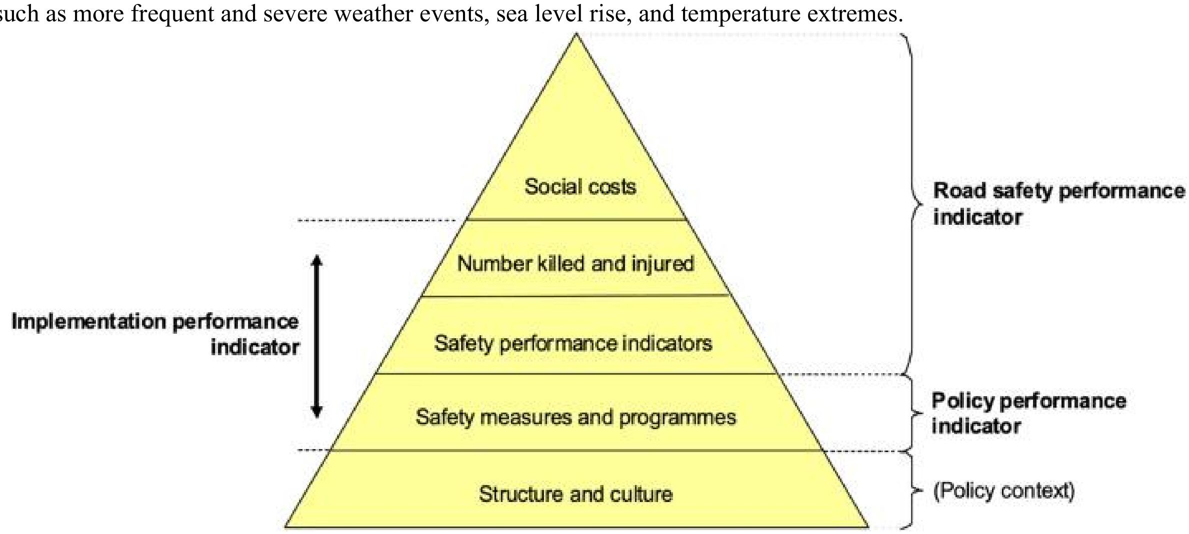

Figure 1- Conceptual frame for highway

Enhance ecosystem services: While highways inherently disturb natural environments, sustainable projects can also incorporate features that provide ecological benefits. This includes stormwater management systems that reduce runoff and improve water quality, wildlife crossings that maintain habitat connectivity, and roadside vegetation that supports pollinators and other species. Sustainable highway landscaping practices can even sequester carbon, reduce urban heat island effects, and provide aesthetic and recreational value.

(ii) Sustainability Frameworks and Rating Systems - To operationalize sustainability principles in the highway sector, various frameworks and rating systems have been developed to guide planning, design, and decision-making. These tools provide structured approaches for assessing and scoring the sustainability of highway projects based on a range of environmental, social, and economic criteria. Some prominent examples include:

Envision: Developed by the Institute for Sustainable Infrastructure (ISI), Envision is a comprehensive framework for evaluating the sustainability of all types of infrastructure, including highways. It consists of 64 sustainability criteria organized into five categories: Quality of Life, Leadership, Resource Allocation, Natural World, and Climate and Resilience. Projects can achieve Envision verification at four levels (Verified, Silver, Gold, Platinum) based on their assessed performance (Institute for Sustainable Infrastructure, 2021).

Greenroads: Greenroads is a sustainability rating system specifically designed for roadway projects, including highways, local roads, and multi-use paths. Developed by the Greenroads Foundation, it evaluates projects based on mandatory prerequisites and voluntary credits across seven categories: Project Requirements, Environment & Water, Construction Activities, Materials & Design, Utilities & Controls, Access & Equity, and Creativity & Effort. Projects can earn Greenroads certification at four levels (Bronze, Silver, Gold, Evergreen) (Greenroads, 2022).

Sustainable Transportation Analysis and Rating System (STARS): Developed by the North American Sustainable Transportation Council (STC), STARS is a planning framework and rating system for assessing the sustainability of transportation plans and projects across modes. It evaluates performance in 12 sustainability goals related to integrated process, access, climate change, ecological function, cost effectiveness, energy, equity, health, land use, material use, safety, and economic benefit. Plans and projects can achieve STARS certification at four levels (Bronze, Silver, Gold, and Platinum) based on their evaluation score (Sustainable Transportation Council, 2021).

Rating System	Developed By	Key Categories/Criteria	Certification Levels	Applicability
Envision	Institute for Sustainable Infrastructure (ISI)	Quality of Life, Leadership, Resource Allocation, Natural World, Climate and Resilience	Verified, Silver, Gold, Platinum	All infrastructure projects, including highways
Greenroads	Greenroads Foundation	Project Requirements, Environment & Water, Construction Activities, Materials & Design, Utilities & Controls, Access & Equity,	Bronze, Silver, Gold, Evergreen	Roadway projects, including highways, local roads, and multi-use paths

Table 1- Comparison of major sustainability rating systems for highway

III. LITERATURE REVIEW

The assessment of environmental sustainability in highway construction and maintenance has garnered increasing attention in recent years as the transportation sector grapples with its significant ecological footprint. This chapter provides a comprehensive review of the existing literature on sustainability assessment frameworks, indicators, and practices in the highway context. It begins by tracing the evolution of sustainability thinking in transportation and highlighting key milestones and policies. The chapter then delves into the various sustainability rating systems and tools that have been developed specifically for highway projects, comparing their scope, criteria, and applications. It also examines the state of practice in assessing and mitigating the environmental impacts of highway construction and maintenance activities, such as material selection, energy use, emissions, water management, and biodiversity conservation. The chapter identifies common challenges and barriers to implementing sustainable practices in the highway sector and explores strategies for overcoming them. Finally, it synthesizes the knowledge gaps and future research directions that emerge from the literature review.

The concept of sustainability, defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987), has gradually permeated the transportation sector over the past few decades. Early efforts focused on reducing air pollutant emissions from vehicles through fuel efficiency standards and emissions control technologies (Lidicker et al., 2013). The 1990s saw a growing recognition of the broader environmental impacts of transportation infrastructure, such as habitat fragmentation, water pollution, and resource depletion (Forman & Alexander, 1998). This led to the development of environmental impact assessment (EIA) regulations and processes for transportation projects in many countries (Spellerberg, 1998). The early 2000s marked a turning point in transportation sustainability with the emergence of the "triple bottom line" framework, which emphasized the integration of economic, social, and environmental considerations in decision-making (Elkington, 1997). Transportation agencies began to incorporate sustainability principles and performance measures into their long-range plans and project evaluation criteria (Jeon & Amekudzi, 2005). The concept of "green highways" gained traction, focusing on strategies such as recycled materials, stormwater management, and ecosystem conservation (Hirsch, 2011). In the United States, the Green Highways Partnership was launched in 2002 as a collaborative effort among federal and state agencies, industry, and academia to promote sustainable practices in highway development (Osterhues et al., 2006). The 2010s witnessed a proliferation of sustainability rating systems and tools tailored specifically to transportation infrastructure. These included the Greenroads Rating System (Muench et al., 2011), the Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) developed by the Federal Highway Administration (2012), and the Envision framework for sustainable infrastructure (Shivakumar et al., 2014). These tools provided structured approaches for assessing and certifying the sustainability performance of highway projects based on a range of criteria and metrics. They also served as educational and communication tools to raise awareness and drive innovation in sustainable practices (Hirsch, 2012). In recent years, the urgency of climate change mitigation and adaptation has further elevated the importance of sustainability in transportation. The Paris Agreement of 2015 set ambitious targets for reducing global greenhouse gas emissions, with the transportation sector expected to play a significant role (Rogelj et al., 2016). Many countries, states, and cities have developed climate action plans and policies that prioritize low-carbon and resilient transportation infrastructure (Gota et al., 2019). The integration of renewable energy technologies, such as solar roads and electric vehicle charging, into highway projects has gained momentum (Shekhar et al., 2020). There is also growing recognition of the need to address social equity and environmental justice issues in transportation planning and investment (Karner et al., 2020).

IV. KEY SUSTAINABILITY INDICATORS AND METRICS

To effectively assess the environmental sustainability of highways, it is important to identify key indicators and metrics that can be measured and tracked over time. These indicators should be relevant, measurable, and actionable, providing a basis for setting targets, evaluating progress, and informing decision-making.

(i) Greenhouse Gas Emissions - Greenhouse gas (GHG) emissions are a critical sustainability indicator given the significant contribution of the transportation sector to climate change. Highway projects can assess GHG emissions at multiple scales and stages, such as:

- Embodied emissions from materials production and construction activities

- Emissions from maintenance equipment and vehicles over the highway lifecycle
- Emissions from traffic operations, including induced travel demand
- Emissions reductions from supporting low-carbon transportation modes and technologies

Common GHG metrics include total lifecycle emissions (expressed in CO2-equivalent units), emissions per mile of highway, emissions per vehicle mile traveled, and emissions compared to a baseline or alternative scenario. Tools like the Federal Highway Administration's Infrastructure Carbon Estimator (ICE) and PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects) can help quantify the carbon footprint of highway construction and maintenance activities (Federal Highway Administration, 2022b; Horvath, 2022).

Indicator Category	Example Metrics	Measurement Methods	Sustainability Goals
Greenhouse Gas Emissions	- Total lifecycle GHG emissions (CO2e) - Emissions per mile of highway - Emissions compared to baseline	- Life Cycle assessment tools (e.g., ICE, PaLATE) - Emissions modeling and forecasting	- Climate change mitigation - Air quality improvement- Sustainable resource use
Material Use and Recycling	- Percentage of recycled materials used - Quantity of locally sourced materials - Material efficiency measures	- Material quantity tracking and reporting - Recycled material content standards	- Sustainable resource use - Waste reduction- Emissions reduction
Stormwater Management and Water Quality	- Percentage of highway area treated by BMPs - Pollutant removal efficiency of BMPs - Annual runoff volume reduction	- BMP performance monitoring and modeling - Stormwater permit compliance reporting	- Water resource protection - Ecological conservation - Regulatory compliance

Some common sustainability indicators and metrics used in the highway sector include:

Table 2- Key sustainability indicators and metrics for highway

(ii) Material Use and Recycling- The extraction, production, and transportation of highway construction materials like aggregate, asphalt, and concrete have significant environmental impacts related to energy use, emissions, water consumption, and land disturbance. Assessing material sustainability involves metrics such as:

Total material use by weight or volume

Percentage of recycled or reclaimed materials used, such as recycled asphalt pavement (RAP), recycled concrete aggregate (RCA), or ground tire rubber

Percentage of locally sourced materials to reduce transportation impacts

Use of materials with lower embodied energy and emissions, such as warm-mix asphalt or supplementary cementitious materials

Material efficiency measures, such as pavement preservation techniques or design optimization to reduce material quantities

(iii) Stormwater Management and Water Quality - Highways can significantly alter natural drainage patterns and contribute to stormwater runoff pollution, particularly in urban areas with extensive impervious surfaces. Metrics for assessing stormwater management and water quality performance include:

Percentage of highway surface area treated by stormwater best management practices (BMPs), such as bioretention, infiltration basins, vegetated swales, or permeable pavement

Pollutant removal efficiency of stormwater BMPs for key contaminants like total suspended solids, nutrients, metals, and hydrocarbons

Annual stormwater runoff volume reduction through infiltration, evapotranspiration, or reuse

Percentage of highway projects incorporating low-impact development (LID) principles to preserve natural drainage features and minimize impervious surfaces

Compliance with applicable stormwater regulations and permit requirements, such as total maximum daily load (TMDL) targets or National Pollutant Discharge Elimination System (NPDES) permits

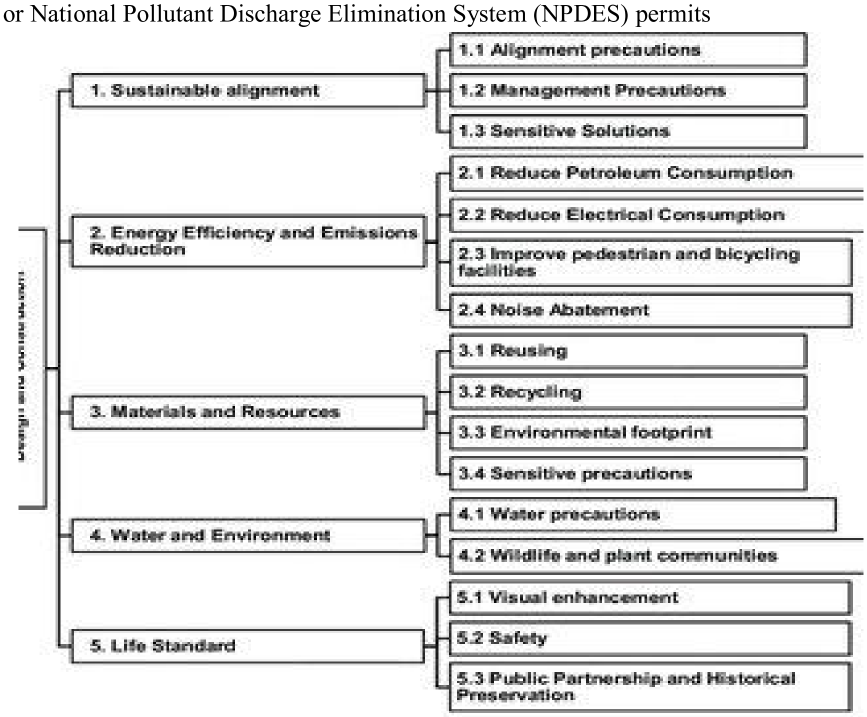

Figure 2- Conceptual diagram of environmental sustainability indicators for highway

V. CONCLUSION

This introductory chapter has set the stage for the dissertation by highlighting the importance and challenges of assessing environmental sustainability in highway construction and maintenance. It has defined key sustainability concepts, principles, and indicators, and reviewed existing assessment frameworks and rating systems. The chapter has also identified significant research gaps and opportunities for advancing sustainability in the highway sector. The environmental impacts of highways are multifaceted and far-reaching, from greenhouse gas emissions and resource depletion to habitat fragmentation and water pollution. As the demand for transportation infrastructure continues to grow globally, it is imperative to develop and implement more sustainable approaches to highway development and operation. This requires a comprehensive understanding of the complex interactions among the technical, economic, institutional, and social dimensions of sustainability in the highway context. Sustainability assessment frameworks and tools, such as Envision, Greenroads, and INVEST, provide valuable guidance and benchmarking for evaluating and improving the sustainability performance of highway projects. However, they also have limitations and challenges, such as the complexity of documentation and verification processes, the lack of contextual sensitivity, and the potential for green washing. It is important to view these frameworks as part of a broader toolkit for sustainability assessment and decision-making, complemented by other forms of analysis, stakeholder engagement, and professional judgment. Advancing sustainability in the highway sector will require a multi-pronged approach that addresses the barriers and leverages the opportunities identified in this chapter. This includes fostering innovation in sustainable technologies, materials, and construction practices, and overcoming institutional, regulatory, and financial hurdles to their implementation. It also involves building capacity and expertise within transportation agencies and the industry, and collaborating with diverse stakeholders to align sustainability goals and actions. The research presented in this dissertation aims to contribute to this ongoing effort by providing a critical assessment of the state of practice, challenges, and opportunities for sustainability in highway construction and maintenance. By synthesizing existing knowledge, evaluating emerging approaches, and engaging with practitioners and stakeholders, the research seeks to offer actionable recommendations and insights for transportation professionals and policymakers.

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